# Hydrological Modeling and Climate Change Impact Assessment Using HBV Light Model: A Case Study of Karnali River Basin

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*A B S T R A C T*

This study has simulated climate change impacts on the runoff processes of the Karnali River Basin of Nepal. Estimation of the variation of snowmelt contribution to streamflow in increased temperatures has been done. The semi-distributed HBV rainfall-runoff model has been calibrated using hydro-meteorological data available from 1986 to 1997. The model simulates runoff based on precipitation, air temperature and potential evapotranspiration. The calibrated model is fed with the climatic projections developed using the PRECIS Regional Climate Model to estimate future (2040s) streamflow. The study indicates that the growing temperatures will generally result in wetter flow regime in the future.

## INTRODUCTION

Increase in the atmospheric contents of greenhouse gases (GHGs) due to rapid industrialization brings change in the radiative balance of the earth resulting in climate change, especially in terms of increase in temperature, change in precipitation pattern and rise in the frequencies of extreme events. Extraordinary warming in the past two decades is believed to be due to the anthropogenic impact [1, 2]. Meteorological data of the previous century suggest a global mean temperature rise of 0.07°C/decade [3]. Globally observed annual precipitation has reportedly increased by up to 0.98% per decade in the twentieth century [4]. The intensity of extreme events has also increased worldwide [5]. The frequency of severe floods in large river basins has increased during the 20th century [6].

Such climatic changes are likely to affect the hydrological processes of many parts of Nepal as well. Nepal's topography extends between the Himalayan ranges (with altitude upto 8848 masl) in the north to the lower southern planes (with altitude as low as around 300 masl)The country's climate is strongly affected by this variation. The lowland regions have a warm sub-tropical climate, with temperature varying around 22-27°C during summer and 10-15°C in the winter. The high altitude mountainous regions are considerably colder with temperatures around 5-15°C in summer and well below zero in the winter. Monsoon rainfall arrives in June and continues until August-September, bringing 250-450

mm of rain/month in most parts of the country but only 100-150 mm in the north-western mountain regions [7].

Changes in flow patterns and magnitude in the major river systems of Nepal are likely to cause reduced water flows in the dry season and flood problems in the wet season. Frequency and magnitude of extreme events like floods and droughts have increased recently [7]. Such adverse situations suggest a need to investigate the impacts of climate change on the water resources at present and in the future in order to conceptualize better strategies for water resource management. Prediction of snow and glacier melt runoff from the Himalayas is of great importance for effective water resources management in the country. Direct field observations needed for such studies are difficult to carry out due to difficulties in reaching remote locations. This necessitates the formulation of a snow and glacier melt runoff model [8]. Very few hydrological studies have been carried out in the Karnali region of far-western Nepal.

This study has assessed the climate change impact on the streamflow processes in the Karnali River Basin (KRB). To achieve this, fine scaled climate change scenarios developed using the Providing Regional Climate for Impact Studies Regional Climate Model (PRECIS RCM) [9, 10] have been used [11]. Projections from PRECIS RCM are fed into the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model to estimate the river discharge in the present and future climate scenarios. Such projections depend on the future

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changes in emissions of GHGs, which are related to future socioeconomic developments. The Special Report on Emission Scenarios (SRES) [12, 13] include six scenario groups; A1B, A2, B1, B2, A1T and A1F1 [14]. In this study, the A1B scenario of the HadCM3 climate change model has been used to predict changes in the runoff regime in KRB for the time period between 2030 and 2060. Contribution of snowmelt to the total discharge has also been calculated.

## MATERIAL AND METHODS

### Study area

Karnali River Basin (KRB) located in far-western Nepal is the second largest basin of the country. The perennial Karnali River originating from the Mansarovar Lake in China is the longest river in Nepal with a length of 507 km. The 202 Km long, Seti River drains the western part of the catchment and the 264 Km long Bheri River drains the eastern part. The geographical location of the basin is shown in Figure 1.
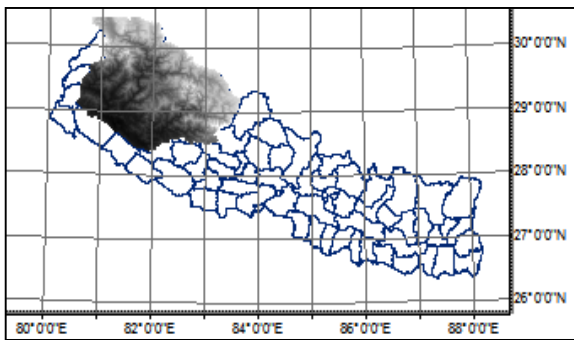


**Figure 1.** Geographical Location of the study area

The basin extends from latitudes 30.4° north to 28.2° south and longitudes 80.6° west to 83.7° east. The catchment extending between the mountain ranges of Dhaulagiri in Nepal and Nanda Devi hills in India has an area of 127,950 km$^2$. The area falling within Nepal is around 41,058 km$^2$ at the outlet of the basin at Chisapani. The watershed's elevation ranges from 140 m to 7498 m. The topography of the basin is characterized by high mountain ranges, steep slopes, terraces and flat valleys. Streamflow is characterized by seasonal variability. Major portion of the total yield occurs in August-September.

Snowmelt is the main contributor to streamflow, which increases during summer. The basin consists of 1,361 glaciers with an area of 1740 km$^2$ and an estimated ice reserve of 127.72 km$^3$.

### The hbv model

The HBV model is a semi-distributed conceptual rainfall-runoff model. It simulates streamflow using rainfall, temperature and potential evapotranspiration (PET) as input [15]. Mean catchment elevation and elevation of precipitation and temperature stations are also specified. HBV-Light [16], a recent version of the model has been employed in several studies evaluating the effects of climate change on river basins. The model has 12 parameters that need to be parameterized for calibration. Monte-Carlo (MC) simulations can be performed using random numbers from a uniform distribution within the set ranges for each parameter. The model is subdivided into three routines; snow and glacier routine, soil moisture routine and runoff generation routine.

The snow and glacier routine uses a temperature-index method to calculate snow and ice melt. Input data are daily air temperature and precipitation. Changes in precipitation and temperature with elevation are calculated using the two parameters PCALT [%/100 m] and TCALT [°C/100 m]. The output is the effective precipitation as rainfall and snowmelt which is fed as input into the soil moisture routine. The liquid and solid precipitations are separated using the parameter, threshold temperature (TT) [17]. Snowmelt amount in any time step is calculated as the product of the degree-day factor (Cfmax) and the difference between air temperature and TT, if the air temperature is above TT [18, 19].

Output of the snow and glacier routine is the input into the soil moisture routine [15] which calculates soil moisture storage, infiltration and percolation through the soil. The maximum storage capacity of the soil is determined by the parameter FC (field capacity). Infiltration is calculated as a function of the ratio between actual soil moisture and FC. Parameter BETA accounts for different infiltration characteristics of soils. The smaller the BETA, the more water is sent to the next routine even when soil moisture is small as compared to FC. The routine calculates actual evaporation as a function of the parameter LP (fraction of soil moisture storage above which actual evaporation is supposed to be equal to the potential evaporation).

The model of a single linear reservoir is used for runoff generation. It is a simple catchment description where runoff at any time is assumed to be proportional to the soil water storage at that time step.

Inputs into the model are precipitation, air temperature, runoff, PET and catchment description. Precipitation and temperature data from meteorological stations need to be corrected for measurement errors. Runoff is taken from the selected gauging stations. Catchments can be separated into different elevation/vegetation zones and sub-catchments. HBV-Light uses a warming-up period to set variable values according to the preceding meteorological conditions.

### Methodology
### Data acquisition

The existing streamflow data of various hydrological stations within the basin are obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal. Daily runoff data at these stations for the study period (1986 to 2004) have been analyzed. There are altogether 20 stations in the basin among which eight have been considered. Details of these stations are shown in Table 1. Filling gaps in the dataset is a necessary step to obtain a longer period of continuous data. It was done by a simple approach of arithmetic averaging of the flows during same day of the same months of the preceding and succeeding two years of the year with missing data.

**TABLE 1.** Hydrological stations used in the study

| St. No. | River | Location | Lat. | Long. | Elev. (m) | Area (km²) |
|---------|-------|----------|------|-------|-----------|------------|
| 215 | Humla Karnali | Lalighat | 29.15 | 81.60 | 590 | 15200 |
| 250 | Karnali | Benighat | 28.96 | 81.12 | 320 | 21240 |
| 256.5 | Budhi Ganga | Mangalsen | 29.16 | 81.21 | 506 | 1576 |
| 259.2 | Seti River | Gopaghat | 29.30 | 80.78 | 750 | 4420 |
| 260 | West Seti | Banga | 28.98 | 81.14 | 328 | 7460 |
| 265 | Thulo Bheri | Rimna | 28.71 | 82.29 | 772 | 7084 |
| 270 | Bheri | Jamu | 28.76 | 81.35 | 246 | 12290 |
| 280 | Karnali River | Chisapani | 28.64 | 81.29 | 191 | 42290 |

Precipitation data from 30 Meteorological stations for the period from 1986 to 2004 were collected as shown in Table 2. Precipitation data from the stations were used to derive a time series of mean areal daily precipitation using Theissen polygons. Arithmetic Mean Method and Normal Ratio Method have been used to fill the gaps in the data series to assure data consistency and continuity. Figure 2 shows the selected meteorological and hydrological stations.

Daily maximum and minimum temperatures at four stations (marked with asterisk in Table 2) for the period ranging from 1986 to 2004 were also obtained. Daily temperature has been calculated as the simple average of the maximum and minimum temperatures. Lapse rate of -0.6°C/100 m is used to compute temperature at elevations different from the measuring stations. Average monthly PET data in mm/day have also been obtained.

**Watershed delineation**
The basin has been delineated into eight sub-basins to carry out the modeling at different points as shown in Figure 3 and Table 1.

**TABLE 2.** Meteorological stations used in the study

| SN | Station | Stn. No. | District | Lat. (deg) | Long. (deg) | Elv. (m) |
|----|---------|----------|----------|------------|-------------|----------|
| 1 | Dadeldhura | 104 | Dadeldhura | 29.3 | 80.58 | 1848 |
| 2 | Chainpur(West) | 202* | Bajhang | 29.55 | 81.22 | 1304 |
| 3 | Silgadhi Doti | 203 | Doti | 29.27 | 80.98 | 1360 |
| 4 | Bajura | 204 | Bajura | 29.38 | 81.32 | 1400 |
| 5 | Katai | 205 | Doti | 29 | 81.13 | 1388 |
| 6 | Asara Ghat | 206 | Achham | 28.95 | 81.45 | 650 |
| 7 | Bangga Camp | 210 | Achham | 28.97 | 81.12 | 340 |
| 8 | Khaptad | 211 | Doti | 29.38 | 81.2 | 3430 |
| 9 | Kola Gaun | 214 | Doti | 29.12 | 80.68 | 1304 |
| 10 | Godavari(West) | 215 | Kailali | 28.87 | 80.63 | 288 |
| 11 | Mangalsen | 217 | Achham | 29.15 | 81.28 | 1345 |
| 12 | Thirpu | 302 | Kalikot | 29.32 | 81.77 | 1006 |
| 13 | Jumla | 303* | jumla | 29.28 | 82.17 | 2300 |
| 14 | Guthi Chaur | 304 | Jumla | 29.28 | 82.32 | 3080 |
| 15 | Sheri Ghat | 305 | Kalikot | 29.13 | 81.6 | 1210 |
| 16 | Gam Shree Nagar | 306 | Mugu | 29.55 | 82.15 | 2133 |
| 17 | Rara | 307 | Mugu | 29.55 | 82.12 | 3048 |
| 18 | Nagma | 308 | Kalikot | 29.2 | 81.9 | 1905 |
| 19 | Bijayapur (Raskot) | 309 | Kalikot | 29.23 | 81.63 | 1814 |
| 20 | Dipal Gaun | 310 | Jumla | 29.27 | 82.22 | 2310 |
| 21 | Simikot | 311 | Humla | 29.97 | 81.83 | 2800 |
| 22 | Dunai | 312* | Dolpa | 28.93 | 82.92 | 2058 |
| 23 | Pusma Camp | 401 | Surkhet | 28.88 | 81.25 | 950 |
| 24 | Dailekh | 402 | Dailekh | 28.85 | 81.72 | 1402 |
| 25 | Jamu (Tikuwa Kuna) | 403 | Surkhet | 28.78 | 81.33 | 260 |
| 26 | Jajarkot | 404 | Jajarkot | 28.7 | 82.2 | 1231 |
| 27 | Chisapani(Karnali) | 405 | Bardiya | 28.65 | 81.27 | 225 |
| 28 | Surkhet | 406* | Surkhet | 28.6 | 81.62 | 720 |
| 29 | Bale Budha | 410 | Dailekh | 28.78 | 81.58 | 610 |
| 30 | Shyano Shree | 413 | Bardiya | 28.35 | 81.7 | 510 |
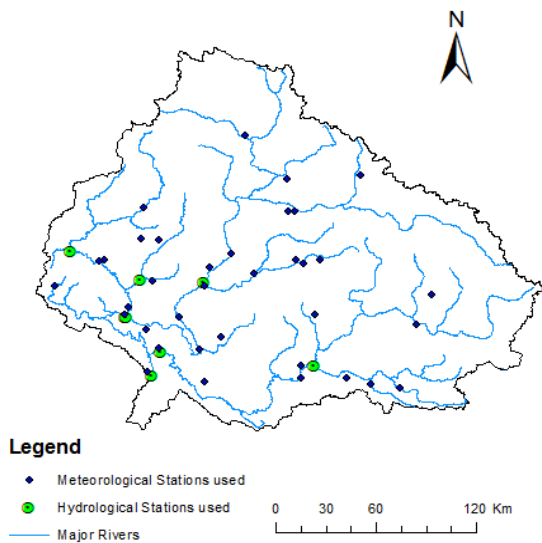
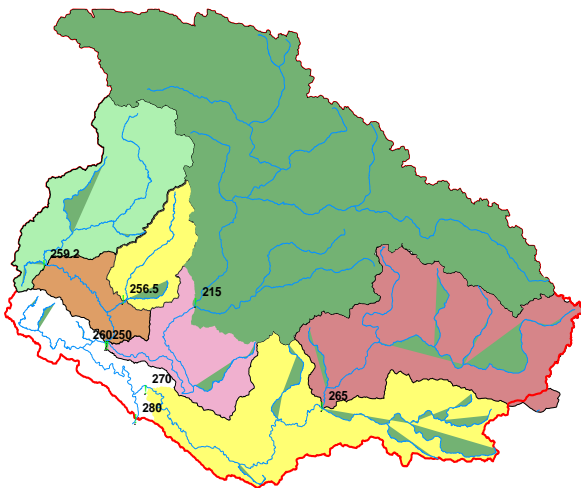**Figure 2.** Meteorological and discharge stations in the area



**Figure 3.** Sub-basins delineated at selected gauging stations

## Model execution

Daily records of mean flow, temperature, precipitation and PET from 1986 to 1997 were used as input for model calibration and records from 1998 to 2004 have been used for model validation. Warming-up period from 1986 to 1987 has been used to allow for adjustments to the initial and boundary conditions. Calibration has been done to obtain the best process parameters for each sub-basin.

Then, assessment of snowmelt is done, which helps in computation of snowmelt contribution to the streamflow. Finally, the calibrated model is run to simulate the future runoff processes in the basin and change in flow regime as compared to a historic base period. The model has been forced with the statistically downscaled climate data of the Had CM3 GCM and the

A1B climate scenario to simulate the streamflow processes for the control period (1970 to 2000) and the future period (2030 to 2060). Temperature and precipitation from the control period of the scenario has been input into the calibrated model. Similar procedure has been carried out to obtain runoff for the future period. Hydrological behavior of the basin has been compared over the two time periods.

## Model calibration

The Nash Sutcliffe (NS) efficiency criterion has been employed as the likelihood measurement for calibration of the parameter sets. NS score for a perfect fit between observed and modeled flows is 1. The criteria is biased towards higher flows because the largest residuals tend to be found near the hydrograph peaks, and as the errors are squared, greater weight is given to prediction of the peaks of the hydrograph [20, 21].

The range of the parameter values was initially specified and sampling was done by 5000 Monte–Carlo (MC) runs specifying 0.6 as the threshold value for each sub-catchment. Table 3 shows the number of sets of parameters yielded that gave acceptable NS scores and also the minimum, mean and maximum values of NS scores from all simulations.

Parameter values obtained from the simulations are optimized manually for the best NS scores, Coefficient of Determination (CoD) and Mean Difference (MD) between observed and simulated flows. Table 4 shows the calibrated parameter values for all sub-catchments.

**TABLE 3.** Summary of the MC simulations

| Sub catchment (Stn. No.) | Thres-hold value of NS | No. of NS values above Thres hold | Min | Mean | Max |
|---|---|---|---|---|---|
| 215 | 0.6 | 223 | 0.61 | 0.643 | 0.72 |
| 250 | 0.75 | 376 | 0.75 | 0.799 | 0.875 |
| 265 | 0.65 | 123 | 0.67 | 0.71 | 0.77 |
| 270 | 0.75 | 220 | 0.75 | 0.82 | 0.86 |
| 256.5 | 0.6 | 287 | 0.63 | 0.66 | 0.73 |
| 259.2 | 0.6 | 62 | 0.6 | 0.64 | 0.69 |
| 260 | 0.7 | 361 | 0.7 | 0.76 | 0.798 |
| 280 | 0.8 | 166 | 0.81 | 0.84 | 0.87 |

Oil palm trunk particles were obtained from Encore Agricultural Industries Sdn Bhd, Malaysia. Polylactic acid (PLA) used in this study were commercially purchased from Synocell Technology. The fire retardant additives such as calcium sulfate ($CaSO_4$) and magnesium oxide (MgO) were purchased from Bendosen. The PLA, $CaSO_4$ and MgO in the form of powder were added at rates of 10% [11] based on oven

dried weight of the particles and manually mixed. Fine particles were manually formed and pre-pressed into homogenous single-layer mat using a forming box of dimension 20.5 cm x 20.5 cm at thickness level of 10 mm to manufacture particleboards. The mats were then pressed at a temperature of 180 °C for 20 min with a pressure of 5 MPa and a target density of 0.80 g/cm³ [11].

**TABLE 4.** Optimized model parameters

| Parameter Catchment (Stn. No.) | PERC | UZL | K0 | K1 | K2 | MAX BAS |
|---|---|---|---|---|---|---|
| 215 | 6.43 | 69.76 | 0.64 | 0.37 | 0.03 | 1.68 |
| 250 | 4.01 | 20.34 | 0.26 | 0.18 | 0.02 | 1.46 |
| 265 | 8.50 | 20.00 | 0.01 | 0.10 | 0.05 | 1.35 |
| 270 | 7.53 | 47.86 | 0.41 | 0.13 | 0.03 | 2.30 |
| 256.5 | 4.64 | 37.95 | 0.12 | 0.02 | 0.01 | 2.17 |
| 259.2 | 5.54 | 96.59 | 0.11 | 0.05 | 0.01 | 1.53 |
| 260 | 3.06 | 68.92 | 0.26 | 0.19 | 0.01 | 1.71 |
| 280 | 4.46 | 12.47 | 0.11 | 0.02 | 0.03 | 1.52 |

| Parameter Catchment | TT | CFMAX | SFCF | FC | LP | BETA |
|---|---|---|---|---|---|---|
| 215 | -3.27 | 2.26 | 1.28 | 296 | 0.95 | 1.68 |
| 250 | -3.00 | 3.17 | 0.26 | 131 | 0.99 | 1.46 |
| 265 | -4.50 | 3.22 | 1.36 | 551 | 0.75 | 1.35 |
| 270 | -6.78 | 2.95 | 0.11 | 650 | 0.51 | 2.30 |
| 256.5 | -5.41 | 0.55 | 0.09 | 92.0 | 0.95 | 2.17 |
| 259.2 | -4.83 | 2.89 | 0.16 | 90.1 | 0.40 | 1.53 |
| 260 | -3.04 | 1.27 | 0.67 | 442 | 1.00 | 1.71 |
| 280 | -2.58 | 3.97 | 0.15 | 275 | 1.00 | 1.52 |

For each condition, there were three replicates and total 12 boards were manufactured. Each sample was weighed and its dimensions of 5 cm x 5 cm x 1 cm were measured to determine their target density. The physical and mechanical properties of panels were evaluated by measuring the thickness swelling (TS), modulus of rupture (MOR) and internal bonding strength (IB) according to Japanese Industrial Standard [12]. Modulus of rupture of the panels were determined on samples with dimension of 50 mm x 150 mm by employing Instron Testing System equipped with a load cell having 1000 kg capacity. Samples with dimension of 50 mm x 50 mm were used for IB strength and thickness swelling of the specimen. Flammability of fire retardant board was determined by measuring limiting oxygen index (LOI) according to ASTM D 2863 [13] under control atmosphere with each specimen having 9 replicates.

## RESULTS AND DISCUSSION

The threshold temperature (TT) is a critical model parameter because simulations show that most of the precipitation under freezing conditions occurs as snow. On the other hand, most of the runoff is generated in summer when temperature is above freezing point. Table 5 shows the NS scores, CoD, observed and simulated discharge during the calibration period and their MD. The NS values are within acceptable range. Figures 4-7 show the observed and simulated discharge during the calibration period for selected sub-basins (Bheri, Seti and Karnali River at Benighat and Chisapani). Observed hydrograph is shown in black and simulated hydrograph in blue. It is seen that the model generally underestimates the peak values while the low flow is better simulated.

**TABLE 5.** Calibration performance of the model

| Basin | Water Balance [mm/year] | | Goodness of fit | | |
|---|---|---|---|---|---|
| | Sum Qsim | Sum Qobs | CoD | NS | MD |
| 215 | 528.23 | 573.89 | 0.64 | 0.63 | 45.65 |
| 250 | 772.37 | 809.59 | 0.81 | 0.77 | 37.22 |
| 265 | 731.83 | 773.72 | 0.77 | 0.71 | 41.89 |
| 270 | 853.26 | 890.56 | 0.86 | 0.84 | 37.29 |
| 256.5 | 1374.24 | 1386.22 | 0.73 | 0.67 | 11.98 |
| 259.2 | 1706.22 | 1727.83 | 0.67 | 0.63 | 21.61 |
| 260 | 1173.27 | 1191.01 | 0.77 | 0.77 | 17.73 |
| 280 | 904.23 | 965.44 | 0.87 | 0.82 | 61.15 |
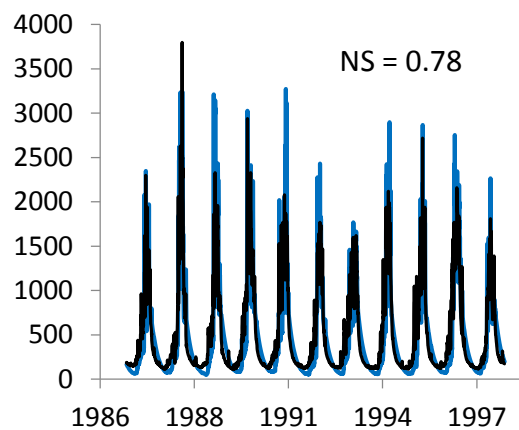


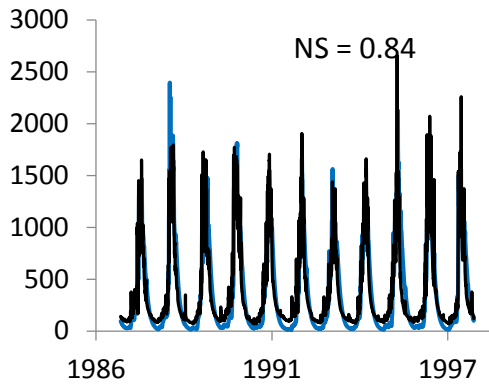**Figure 4** Observed and simulated discharge (mm/day) at Karnali at Benighat

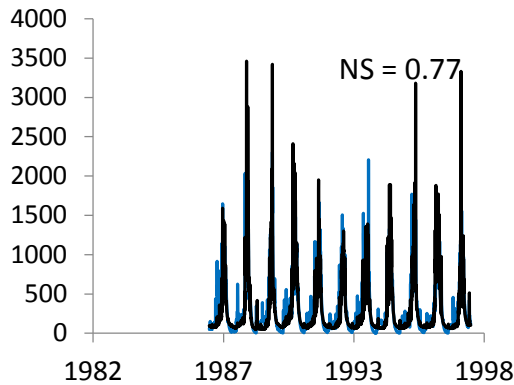**Figure 5.** Observed and simulated discharge (mm/day) at Bheri at Jamu



**Figure 6.** Observed and simulated discharge (mm/day) at Seti at Bel Gaon
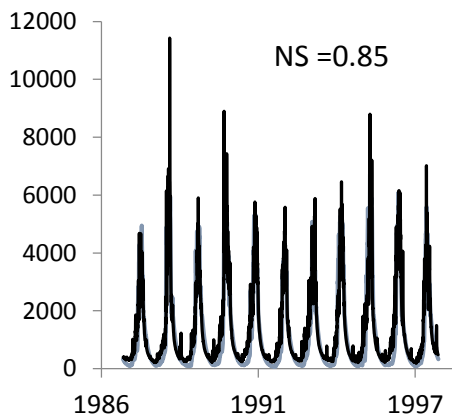


**Figure 7.** Observed and simulated discharge (mm/day) at Karnali at Chisapani

Table 6 shows the model performance for the validation period. Acceptable range of NS scores and CoD indicates the robustness of the model.

**TABLE 6.** Validation performance of the model

| Basin | Water Balance [mm/year] | | Goodness of fit | | |
|---|---|---|---|---|---|
| | Sum Qsim | Sum Qobs | CoD | NS | MD |
| 215 | 592.52 | 533.84 | 0.78 | 0.71 | -58.68 |
| 250 | 781.35 | 890.92 | 0.80 | 0.79 | 109.56 |
| 265 | 883.76 | 870.56 | 0.74 | 0.61 | -13.20 |
| 270 | 983.97 | 990.07 | 0.78 | 0.78 | 6.10 |
| 256.5 | 1581.03 | 1845.63 | 0.72 | 0.72 | 264.61 |
| 259.2 | 1383.85 | 1466.22 | 0.66 | 0.66 | 82.37 |
| 260 | 1293.19 | 1272.21 | 0.75 | 0.75 | -20.97 |
| 280 | 919.97 | 1117.19 | 0.87 | 0,87 | 197.21 |

Results indicate close proximity between observed and simulated runoff at different locations. This demonstrates that the calibrated parameters are satisfactory and can be used to simulate the streamflow for any independent time period.

**Snowmelt contribution to total runoff**
The model has been used to assess the contribution of snowmelt to total discharge at the selected locations. Results show that the contribution of snowmelt to annual flow at the basin outlet is about 11% with a maximum monthly contribution of 30% in May and a minimum of 2% in January. Results show that in almost all sub-catchments, the maximum contribution is maximum from March to July and minimum from November to February. Figure 8 shows the snowmelt contribution in percentage to annual streamflow in various sub-catchments.

Contribution to annual streamflow is highest at Benighat (16% to 18%) and is least in Bheri at Jamu (almost 5%). Snowmelt contribution to annual runoff at Seti River at Bel Gaon shows a varying trend; up to 27% in 1987 and as low as 11% in 1997. As we move further downstream, the contribution is lowest at the outlet at Chisapani.
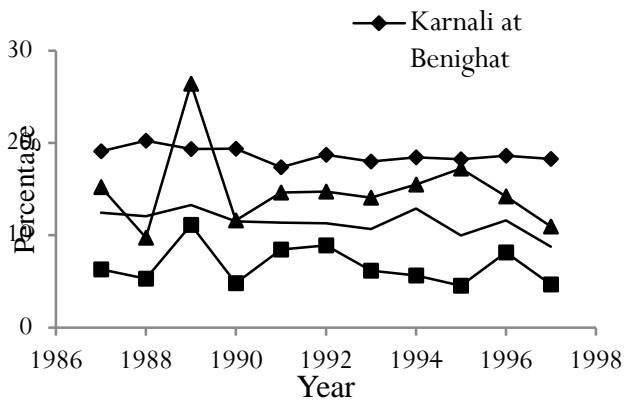
**Figure 8.** Contribution of Snowmelt to annual flow

**Sensitivity tests**

Contribution of snowmelt is estimated for increasing temperature scenarios for which the calibration period is taken as the base period. The model is run for estimating snowmelt by increasing the mean daily temperature by 0.5°C, 1°C and 1.5°C. This sensitivity test has been done for selected stations as shown in Table 7.

**TABLE 7.** Snowmelt contribution (%) to total runoff in increased temperatures

| Station | Period | Increase in temperature (°C) | | | |
|---------|--------|------|------|------|------|
| | | 0 | 0.5 | 1 | 1.5 |
| Karnali (Benighat) | MAMJJ | 28.07 | 38.18 | 39.65 | 40.59 |
| | NDJF | 2.78 | 2.75 | 2.89 | 3.26 |
| | Annual | 19.2 | 21.21 | 22.07 | 22.75 |
| Bheri at Jamu | MAMJJ | 14.87 | 8.25 | 7.37 | 6.43 |
| | NDJF | 5.04 | 5.15 | 5.05 | 5.74 |
| | Annual | 6.73 | 5.31 | 4.91 | 4.74 |
| Seti at Belgaon | MAMJJ | 28.06 | 28.73 | 28.04 | 27.37 |
| | NDJF | 9.78 | 10.16 | 10.72 | 10.78 |
| | Annual | 15.3 | 15.38 | 15.54 | 15.02 |
| Karnali at Chisapani | MAMJJ | 21.75 | 25.31 | 28.39 | 29.49 |
| | NDJF | 2.69 | 2.84 | 3.49 | 3.8 |
| | Annual | 11.44 | 13.61 | 15.63 | 16.57 |

*MAMJJ: March-May, NDJF: November-February*

Results indicate no definite pattern of the increment of snowmelt contribution with increase in temperature. The maximum rate of this increment is observed at Benighat where the contribution is seen to increase at a very high rate from March-July. With an increase of 1.5°C, the snowmelt contribution is seen to increase from 22% to 30% at different seasons at the basin outlet. Contribution

during the winter in all stations is increasing at a much lesser rate. Annual contribution of snowmelt is seen to be most extreme at Benighat and Chisapani with increased temperatures.

**Simulation of future flows**

The model has been forced with the downscaled climate data of the HadCM3 GCM and the A1B climate scenario to simulate streamflow processes for the control period (1970-2000) and the future period (2030-2060). Figures 9-11 show the percentage change in monthly streamflow over the two periods for 3 stations. The model simulates an overall increase in monthly streamflow. In Benighat, the model simulates a high increase in streamflow from January to June (up to 170% of the control values). However, in July-December, the model simulates a conservative increase [20].
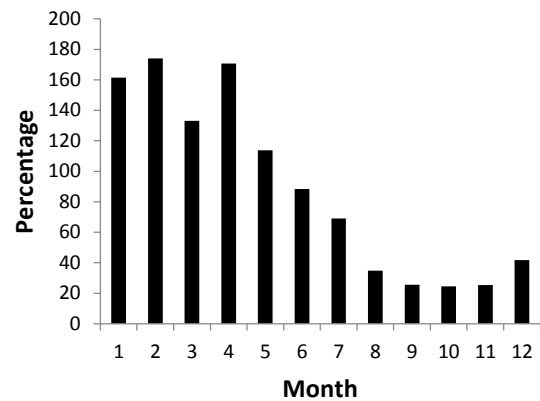


**Figure 9.** Change in future streamflow as compared to control period at Karnali at Benighat
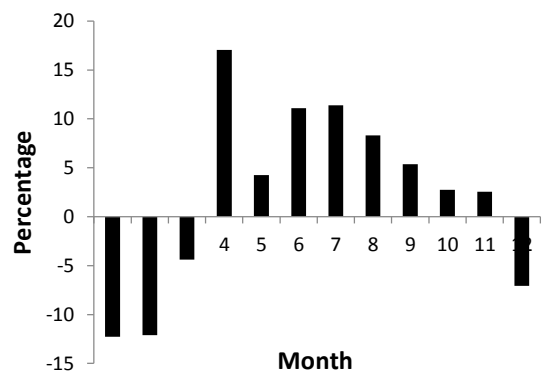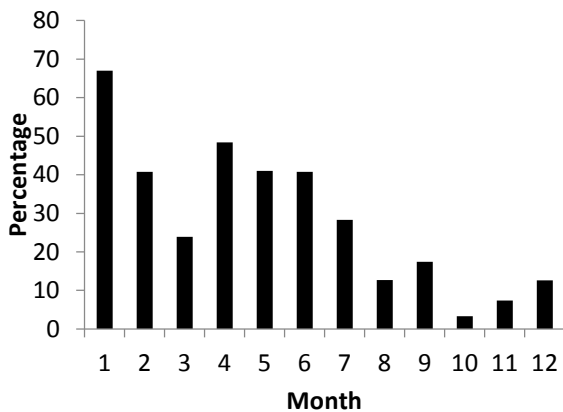


**Figure 10.** Change in future streamflow as compared to control period at Bheri at Jamu

**Figure 11.** Change in future streamflow as compared to control period at Seti at Bel Gaon

At Jamu, the highest percentage increase in monthly streamflow is in April (17%). The largest reduction occurs in January-February. The streamflow from September-November are much nearer to the control values (-2% -−7%). The model simulates a significantly wetter monthly regime, particularly in the main flooding season. This indicates that increasing temperatures will have significant effects in the overall hydrological regime of the basin.

## CONCLUSION

Snowmelt is a major source of runoff in Karnali River Basin, especially from March to July. With the start of summer, snow accumulated in the previous winter begins to melt and feeds the mountainous rivers. Snowmelt occurs mostly from the elevation range between 3000 and 5000 masl. Snow accumulated above this range does not provide significant contribution to streamflow. Snowmelt contribution to the runoff in different seasons at different locations of the basin has been estimated in the study. Choice of the HBV-Light model for the purpose of simulating streamflow and snowmelt has been proven to be effective. The NS-efficiency criterion has shown the effectiveness of the model in simulating rainfall-runoff processes. Model performance is highly sensitive on the initial choice of parameter values. Generation of a large number of parameter sets using MC simulation is useful in prioritizing the important parameters to be used during calibration.

At the basin outlet at Chisapani, snowmelt contribution to annual flow is about 11%. This contribution increases as one moves upstream. It is seen that the maximum contribution is from March-July at different locations in the basin. Result of sensitivity tests demonstrate that increasing temperatures may cause enhancement in the annual and seasonal streamflow and

also in the snowmelt contribution to streamflow. Running the calibrated model with outputs of the HadCM3 RCM simulated significantly wetter monthly regimes in the 2040s. The impact will be highly pronounced in the flooding season. This may have consequences on water abstraction activities, leading to changes in cropping patterns, electricity production and supply of drinking water in the basin, which will have impacts on the economy of the region.

There is a need of more hydro-meteorological stations in the mountainous catchments -where snowmelt forms the major source of annual runoff-for better hydrological simulations. The need of high quality data measurement and analysis becomes more vital during times of population growth and changing socioeconomic activities [22].

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**Persian Abstract**

چکیده

این مطالعه تاثیرات تغییرات آب و هوایی را بر روند رواناب حوضه رودخانه کارنالی نپال شبیه سازی کرده است. تخمین تغییرات سهمیه مایع برف در جریان در دمای بالا افزایش یافته است. مدل بارش باران نیمه توزیع شده HBV با استفاده از اطلاعات هیدرو هواشناسی در دسترس از سال ۱۹۸۶ تا ۱۹۹۷، کالیبراسیون شده است. این مدل شباهت رواناب را براساس بارش، دمای هوا و تبخیر تعرق بالقوه ای شبیه سازی می کند. مدل کالیبراسیون با پیش بینی های آب و هوایی توسعه یافته با استفاده از مدل آب و هوای منطقه ای PRECIS برای تخمین جریان آتی (۲۰۴۰) جریان داده شده است. این مطالعه نشان می دهد که درجه حرارت رو به رشد به طور کلی در آینده موجب افزایش رطوبت می شود.